

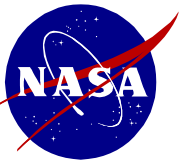
Vector Optical Modelling for Visible Light Coronagraphy

Richard Lyon - NASA/GSFC
Robert Woodruff - LMCO
Ron Shiri - GST
Roman Antosik - CUNY



TPF Technology Expo
October 15, 2003

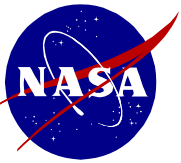
<http://code935.gsfc.nasa.gov/cube%20Folder/OSCAR/index.html>



Contents

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- Synopsis of the Study
- Systems Modeling Approach:
 - Polarization Raytrace
 - Fresnel Diffraction (S & P States)
 - Vector FEM Modeling
 - Component Transfer Functions
 - Systems Level Approach
- What we will model:
 - Occulters/Pupils/Apodizers
 - Amp/Phase/Polychromatic/Microroughness
 - Misalignments/Deformations
 - Design & Manufacturing Errors
- Expected Results:
 - Tabulate differences in Vector vs Scalar
 - When do we need Vector Theory ?
 - Do we have to design w/Vector Theory ?
 - Systems level sensitivities
 - Systems level Error Budgeting
 - Validation => Testbeds
- Summary



Studies

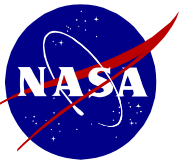
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- *Previous Funded Studies:*

- TPF Architecture Study (Boeing 07/00 - 12/01)
 - IR Interferometer and ASA Coronagraph
- Holographic Speckle Correction (GSFC 2002)
 - Photorefractive Polymers w/coronagraph
- ESP NRA (Woodruff, Ridgway, Lyon et.al, 02/02 - 10/02)
 - Optical design which supports Lyot, SK, ASA
 - Calculate Sensitivities and Error Budget
 - Compare/Contrast Lyot/SK/ASA
 - Woodruff Report (November 2002)

- *Current Study:*

- Development Technologies for the TPF Mission (JPL JYC-572383)
- 2 years w/ optional 3rd year, Oct 2002 - Oct 2004
- Lyon, Woodruff, Shiri, Antosik
- 3 Components to Study:
 1. Vector vs Scalar Diffraction
 2. Static Wavefront Correctors (Fiber Bundle / Phase Plates)
 3. Phase & Amplitude Rectification (PAR) Technique
- Couple via *Component Transfer Functions (Vector FEM)*
- Systems Level Approach => Sensitivities & Error Budgets
- Tabulate Differences between Scalar & Vector Diffn.



Extra-Solar Planetary NRA

Review of Study Results

• ESP NRA (Woodruff, Ridgway, Lyon et.al 02/02 - 10/02)

- Phase I:

- Code V Optical Design (Telescope, AO Bench, Coronagraph)
- OSCAR Model (Code V & OSCAR Raytrace to $< 1e-6$)
- Compare Contrasts of: ASA / Spengel-Kasdin / Lyot Coronagraph
- Calculate Sensitivities and Error Budget

- Major Results (Phase I):

- Contrast Reduction due Mid-freq WFE nearly independent of method !.
- Earths: WFE (3-30 cycles/ap) $< \lambda/10,000$ rms, **Amp Error < 0.03 %**

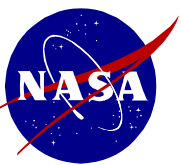
- Amp / Wavefront Errors well modelled by:

$$PSF(\lambda/B) = [1 - \sigma_A^2][1 - k^2 \sigma_{WF}^2] PSF_0(\lambda/B) + \sigma_A^2 PSD_A(\lambda/B) + k^2 \sigma_{WF}^2 PSD_{WF}(\lambda/B)$$

$[1 - \sigma_A^2][1 - k^2 \sigma_{WF}^2]$: Augmented Strehl Ratio with $PSD_A(0) = PSD_{WF}(0) = 1$

σ_A, σ_{WF} : Fraction Amp Error and RMS Wavefront Error

However... All results to date based upon scalar theory



Apodized Square Aperture (ASA)

ESPI - Extra-Solar Planet Imager Proposed Concept

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Square

Sonine

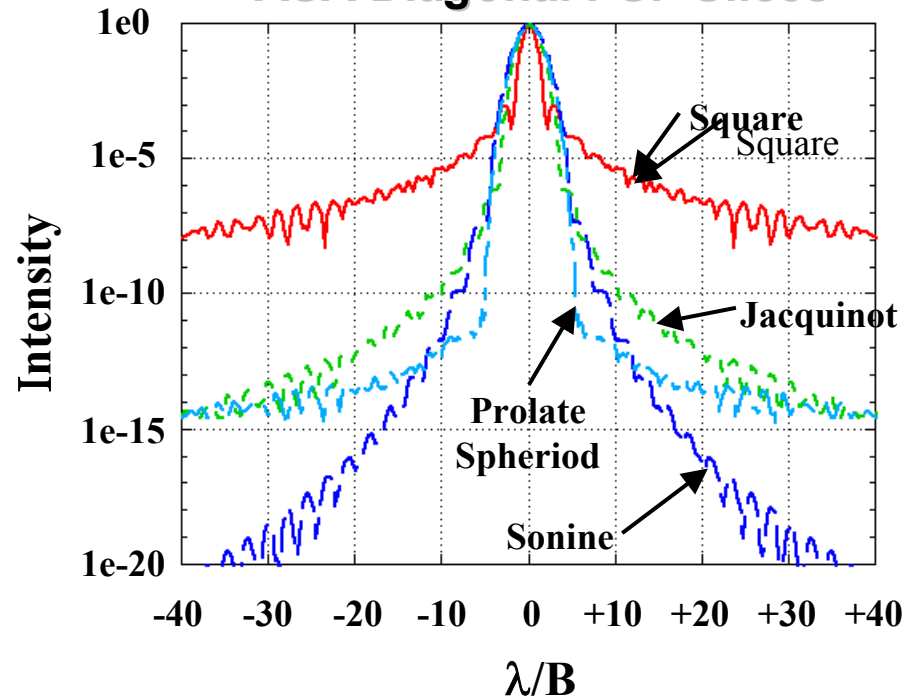
Jacquinot

Prolate
Spheroid

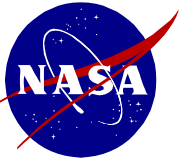
PSFs

Amplitude

ASA Diagonal PSF Slices



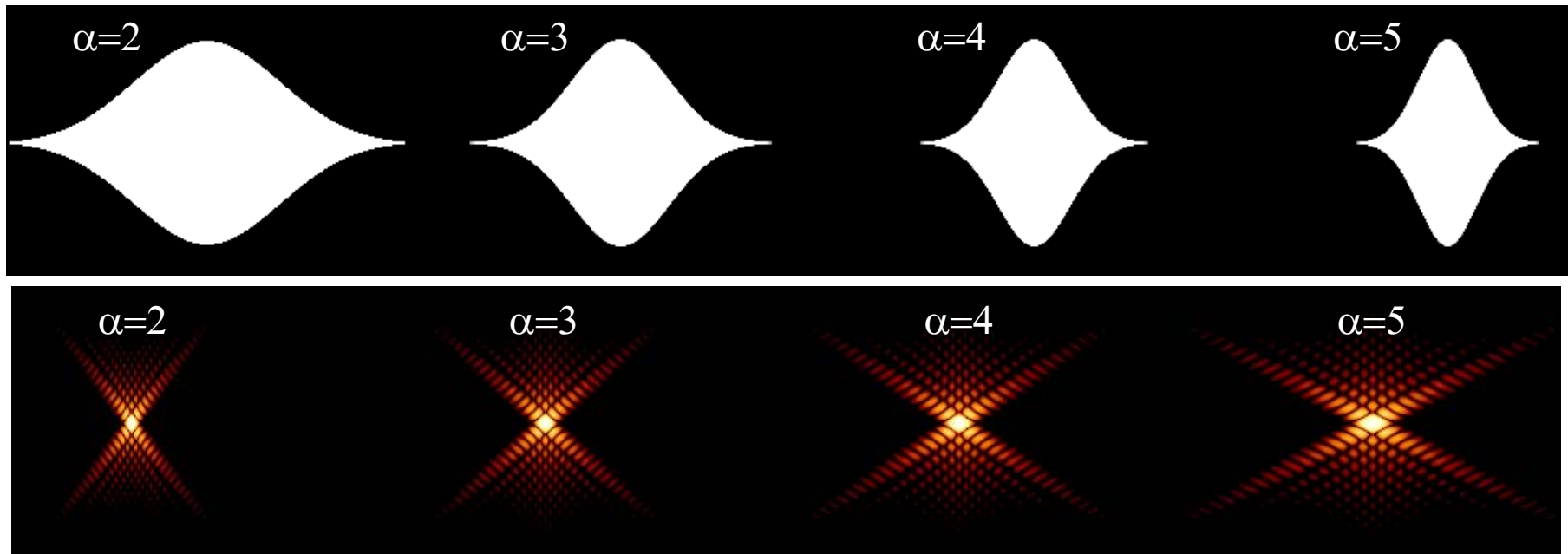
PSFs: $\lambda=0.6 \mu\text{m}$, $\Delta\lambda=0.2 \mu\text{m}$.
PSFs on same log scale and the
Amplitude functions on same linear
scale.



Spergel/Kasdin Pupils

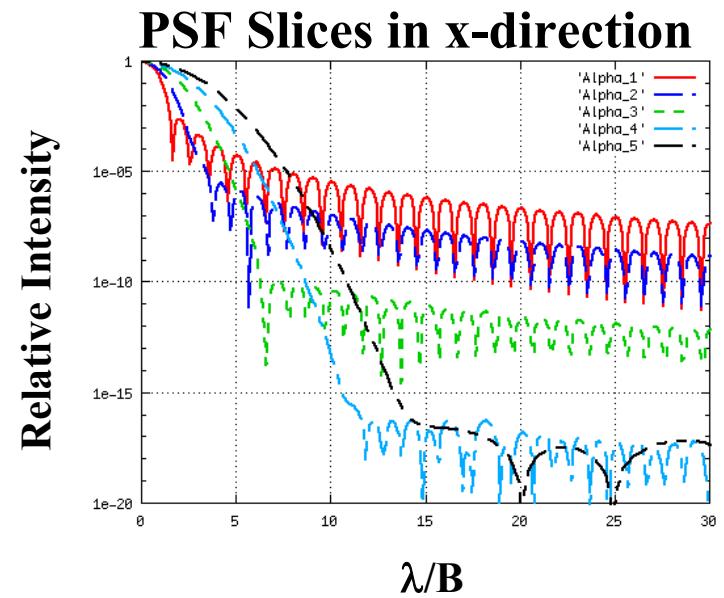
Apertures and PSFs

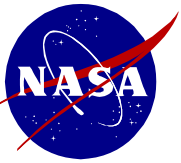
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As α is increases:

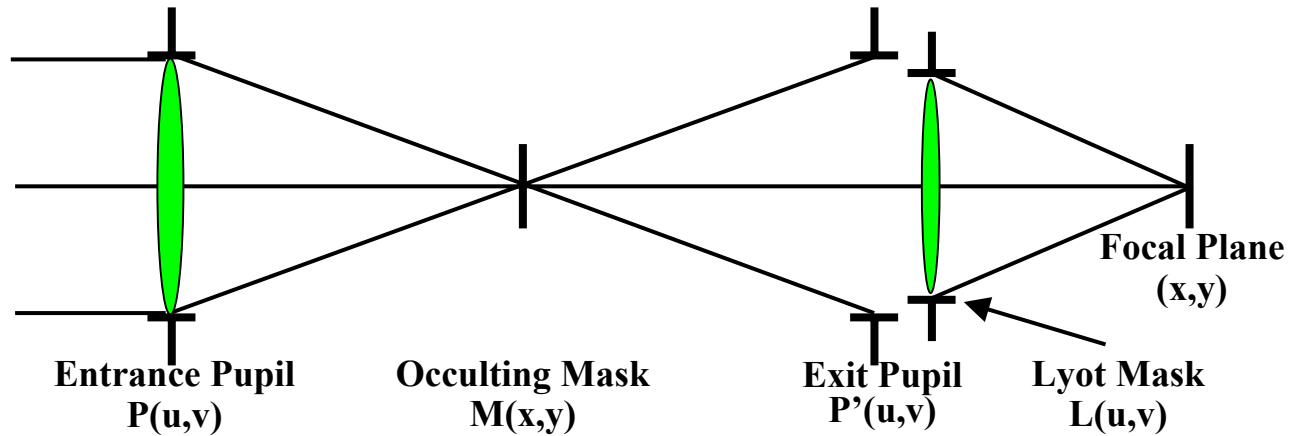
- Pupils narrow in x
- Null zones decrease in area
- Null depth is deeper
- PSF core broadens



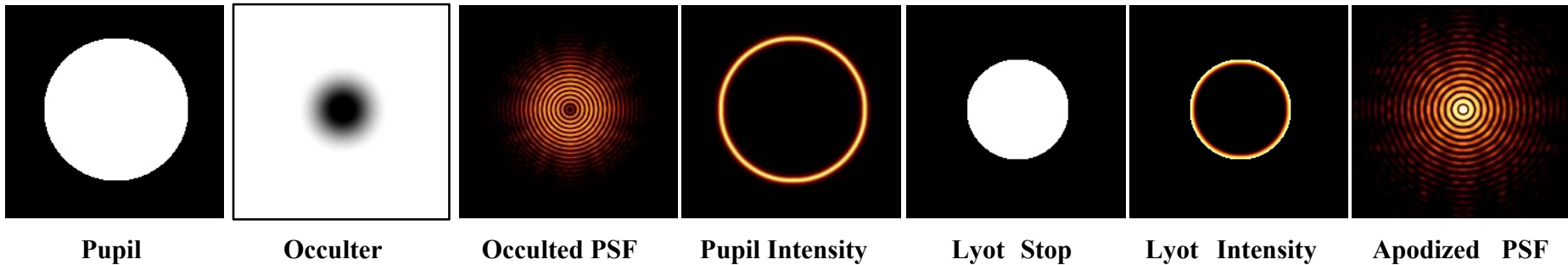


Soft-Edge Lyot Coronagraph

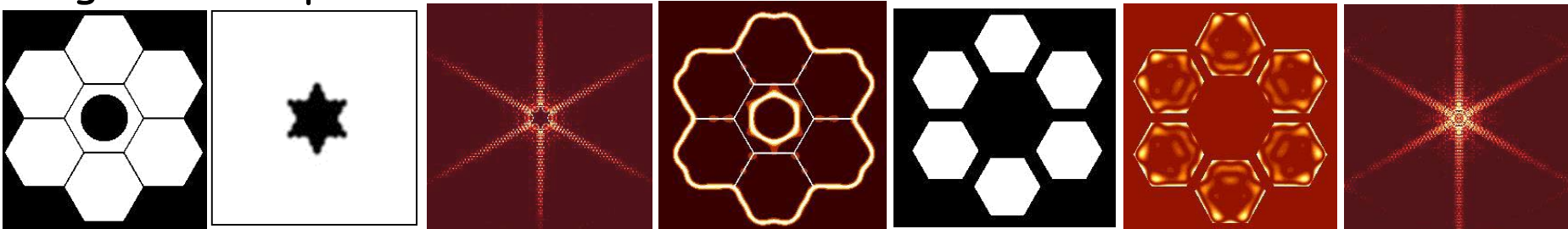
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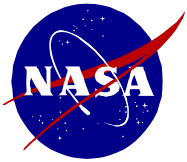


Filled Aperture



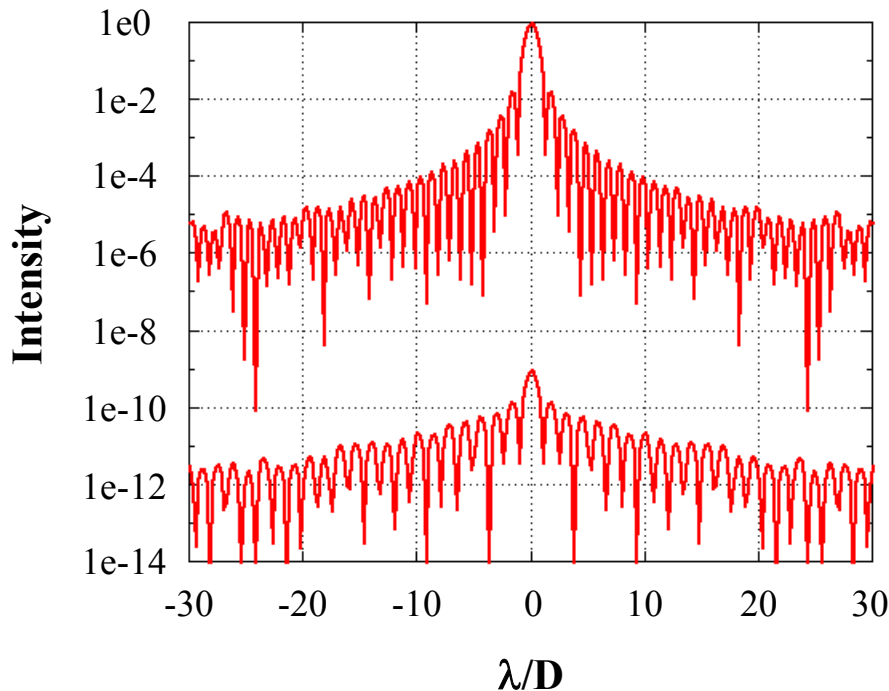
Segmented Aperture





Soft-Edge Occulting Mask PSF

Scalar Diffraction Theory



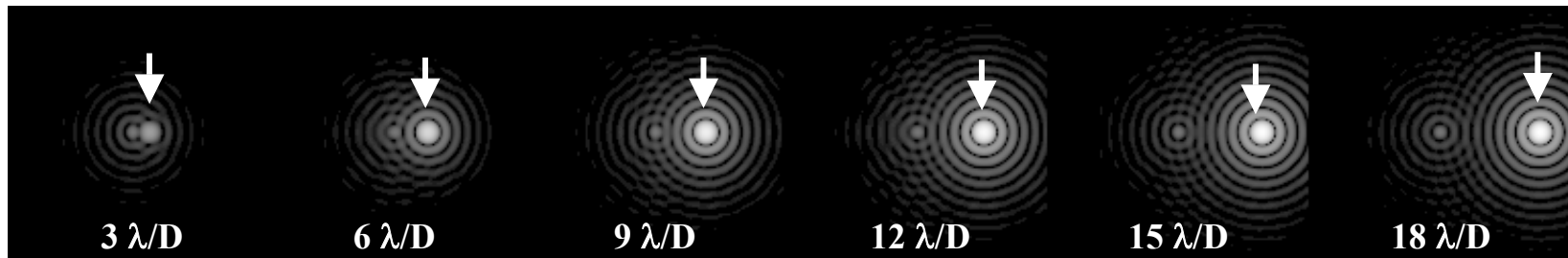
Occulting Mask

$$T(r) = 1.0 - e^{-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2}$$

$$\sigma = 4 \lambda/D$$

Planet/Star at 1e-6 Luminosity Ratio at 75% Lyot Stop

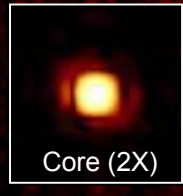
- Soft-edge ring occulting mask, sigma = 4.0 λ/D
- 75% Lyot Stop
- 1e-6 Luminosity Ratio
- Monochromatic
- plots are log-stretched, arrow points to planet.



Speckle

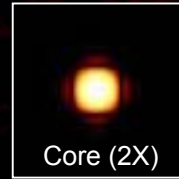
Monochromatic ASA

$D = 5.0$ meters
 $\lambda = 0.5 \mu\text{m}$
 $\sigma = \lambda/100$ rms surface



Monochromatic ASA

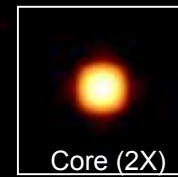
$D = 5.0$ meters
 $\lambda = 0.5 \mu\text{m}$
 $\sigma = \lambda/500$ rms surface



$$\text{Surface PSD} \sim \frac{A}{1 + (f/f_0)^{3.55}}$$

Polychromatic ASA

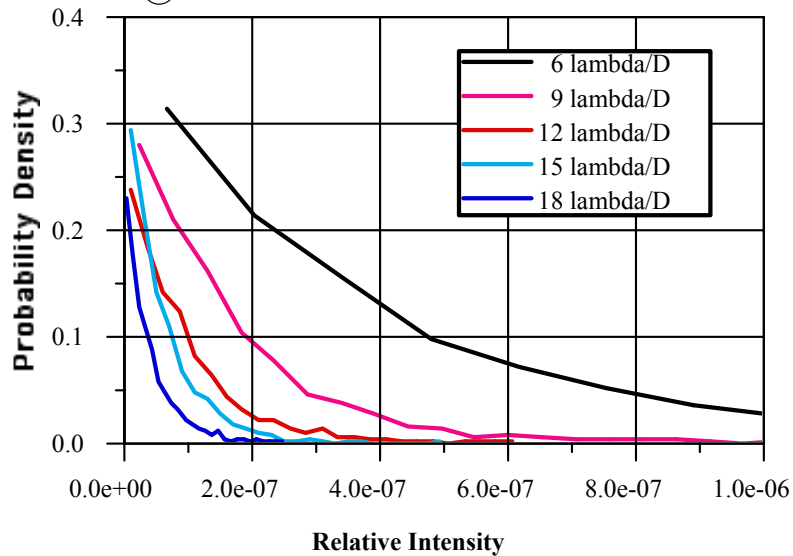
$D = 5.0$ meters
 $\lambda = 0.5 \mu\text{m}$
 $\Delta\lambda = 0.25 \mu\text{m}$ FWHM
 $\sigma = \lambda/500$ rms surface



2.5 arcsec

Speckle Statistics

@ $\lambda/500$ rms WFE



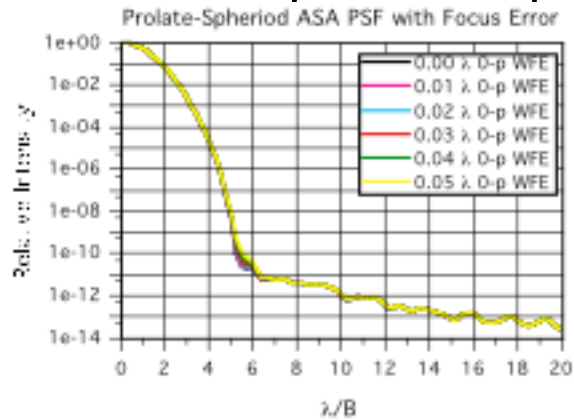
$$P(I) = \frac{1}{\langle I \rangle} \exp\left(-\frac{I}{\langle I \rangle}\right)$$

Variability is $\sim 100\%$ of mean !

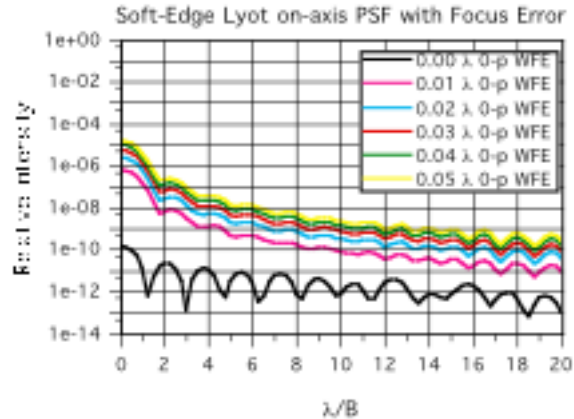
$$\text{mean} = \langle I \rangle$$

$$\sigma_I = \langle I \rangle$$

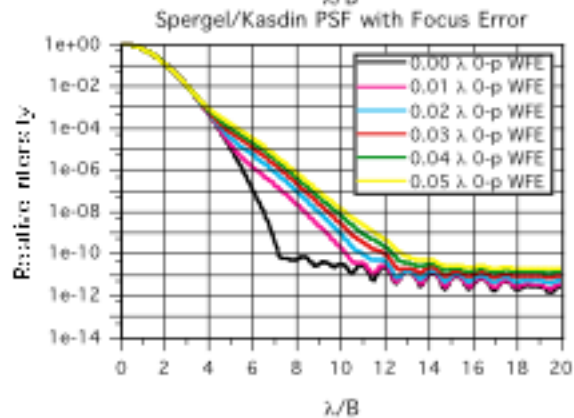
Low-Spatial Freq



ASA PSF
 $\lambda = 0.5 - 0.7 \mu\text{m}$

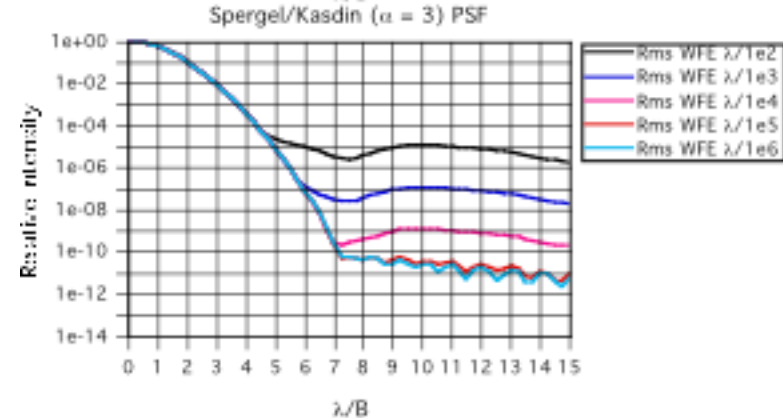
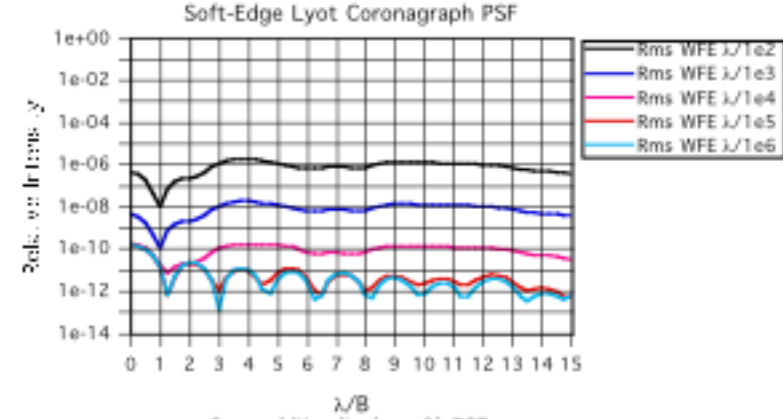
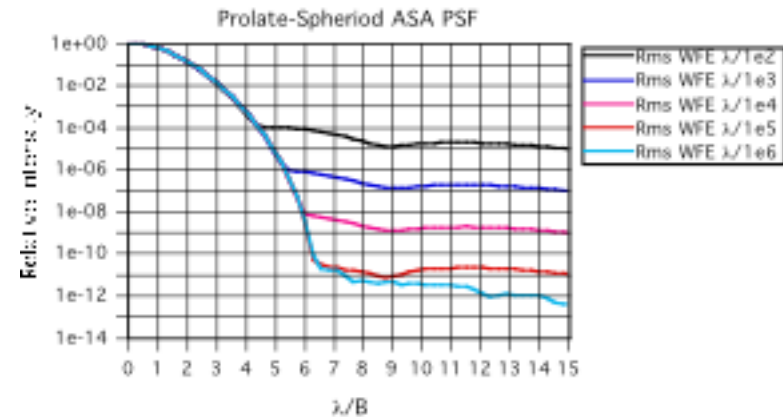


Soft-Edge Lyot PSF
 $\lambda = 0.5 - 0.7 \mu\text{m}$

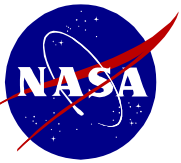


Spergel/Kasdin PSF
 $\lambda = 0.5 - 0.7 \mu\text{m}$

Mid-Spatial Freq



B = Longest Baseline

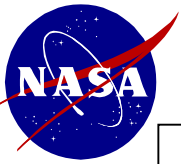


Extra-Solar Planetary NRA

Review of Study Results

- ESP NRA (Woodruff, Ridgway, Lyon et.al 02/02 - 10/02)
 - Initially Studied:
 - Apodized Square Apertures
 - Soft-Edge Lyot Coronagraph
 - Spergel/Kasdin Shaped Pupil
 - Effects of:
 - Polychromatic, Wavefront and Amplitude Errors
 - Jitter, Leakage Errors, Random Shape Errors
 - Misalignments, Low-Freq Errors
 - Tabulated Results in Terms of:
 - Contrast, SNR, Detection Zone
 - Sensitivity Analysis and Error Budgeting
 - Documented Results in:
 - Woodruff, R., Ridgway, S., Lyon, et.al
Feasibility of and Technology Roadmap for Coronagraphic Approaches to TPF Phase I Final Report, NASA NRA-01-OSS-04
Extra-Solar Planets Advanced Mission Concepts Type 3 Study, Nov, 2002
 - **However**... did not contain:
 - Multi-Plane Diffraction (Fresnel)
 - Polarization
 - Full Vector Field Effects on Masks and Occulters
- Development Technologies for TPF (JPL RFP No. JYC-572383)

ALSO:
External Occulters
HyperTelescopes
Labeyrie Corrector



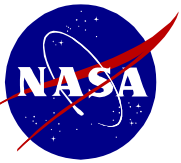
Scalar vs Vector Theory

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Coronagraphs work by Scalar Diffraction Theory

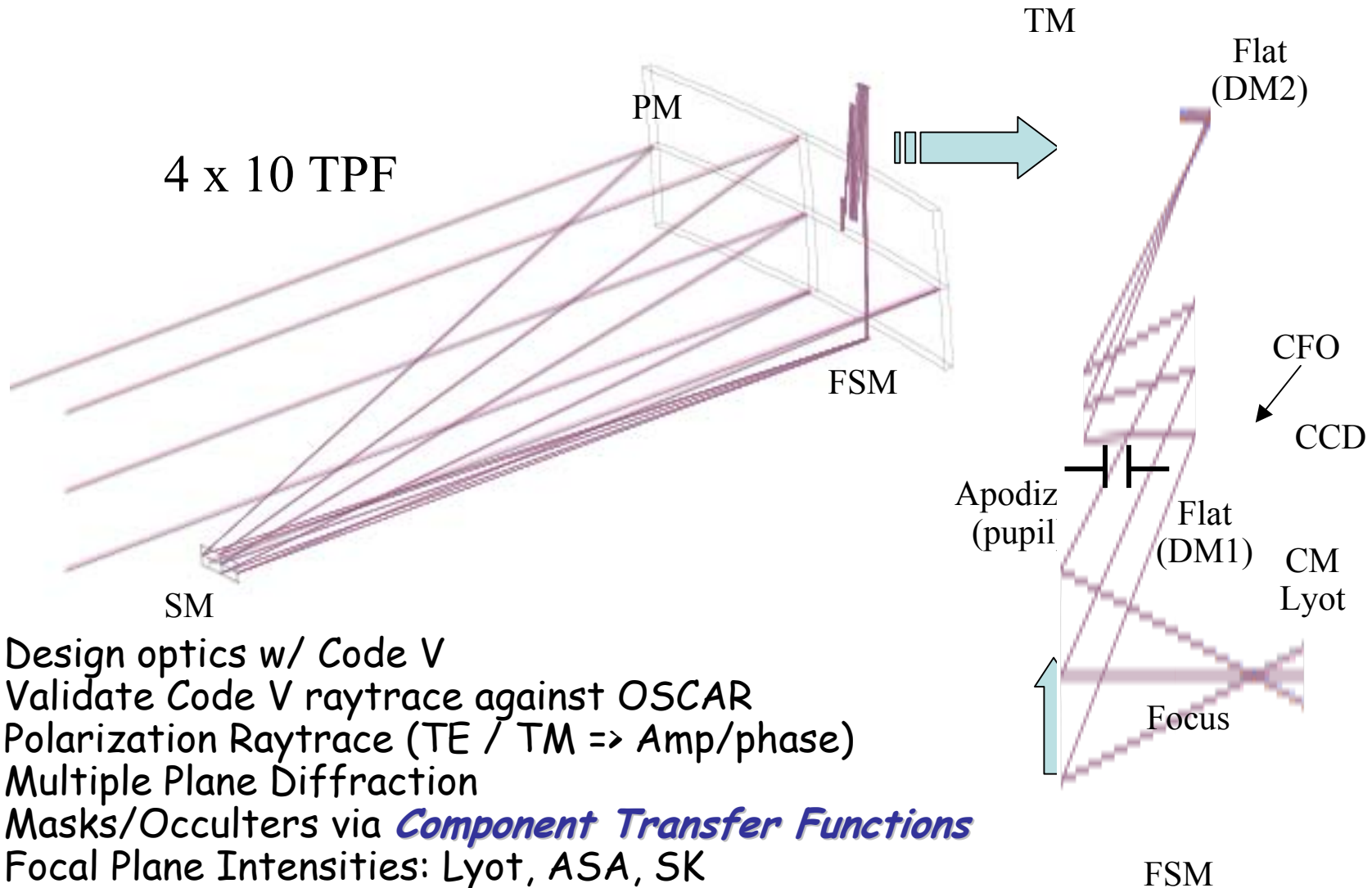
- Scalar Theory is an *approximation*:
 - (1) Maxwell's Equations \Rightarrow Vector fields in $\vec{E}(\vec{r}, t)$ and $\vec{H}(\vec{r}, t)$
 - Scalar theory ignores polarization effects
 - Optics introduce polarization shifts, Amp and WF changes
 - (2) Kirchoff Approximation
 - Masks/occulters \Rightarrow infinitely thin perfect conductors
 - Masks/occulters are 3D finite objects w/ $n = n + ik$
 - (3) Fresnel Approximation
 - 2nd order in phase & paraxial
 - Spherical waves treated as parabolic waves
 - (4) Aberrated Pupil Analysis
 - compresses all phase/amp effects to single diffraction plane.
 - Multiple plane diffraction needed?
- Will Coronagraphs designed w/ Scalar Theory achieve 10^{-10} ?

What are implications of Scalar Theory for TPF ?

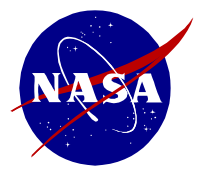


Adopted Full Systems Approach

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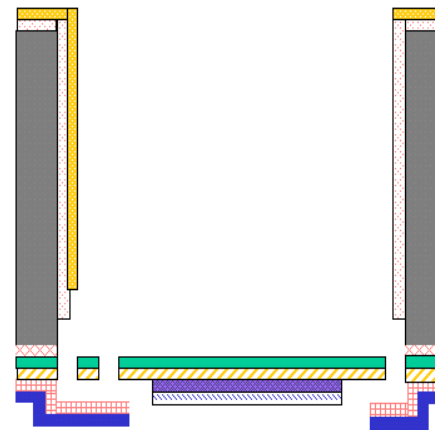
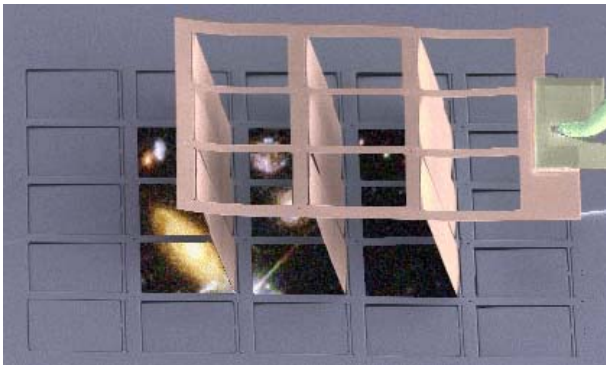
- Design optics w/ Code V
- Validate Code V raytrace against OSCAR
- Polarization Raytrace (TE / TM \Rightarrow Amp/phase)
- Multiple Plane Diffraction
- Masks/Occluders via *Component Transfer Functions*
- Focal Plane Intensities: Lyot, ASA, SK
- Contrast as function of: misalign/deform/etc...
- Compare w/ scalar diffraction aberrated pupil analysis













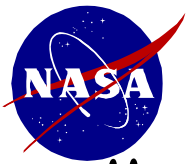
Component Transfer Functions

Past Example: JWST/NIRSpec
Modeling of MEMS Shutter

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	Light Shield: Aluminum		Magnetic Pad: CoFe
	Support Grid: Silicon		Shutter Mechanical Layer: Silicon Nitride
	Etch Stop: Silicon Dioxide		Vertical Electrode: Gold
	Interconnect/Shutter Electrode: Gold		Vertical Electrode Insulator: Aluminum Oxide
	Light Shield Insulator: Silicon Dioxide		Magnetic Pad Passivation: Aluminum



Component Transfer Functions

Modeling of MEMS Shutter

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- Maxwell's Equations are Linear
=> Decompose input field into
Angular plane wave spectrum:

$$C(\alpha) = \int E_{Inc}(x) e^{-i2\pi\alpha(x/\lambda)} dx$$

- Solve Vector FEM for each
Angular Plane Wave:

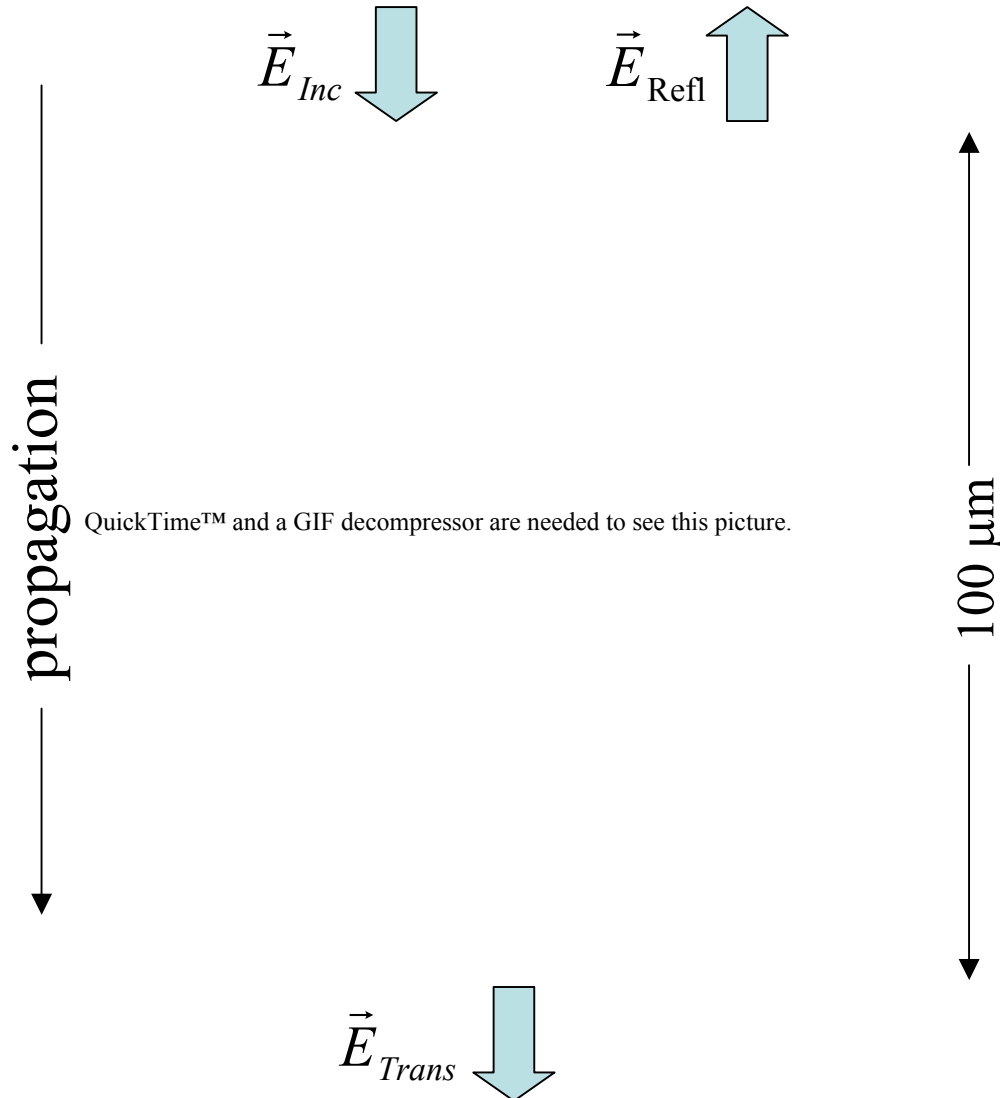
$$E_{Trans}(\alpha, x) = T(\alpha, x) C(\alpha) e^{i2\pi\alpha(x/\lambda)}$$

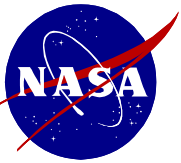
$$T(\alpha, x) = \text{CTF}$$

- Sum over Components

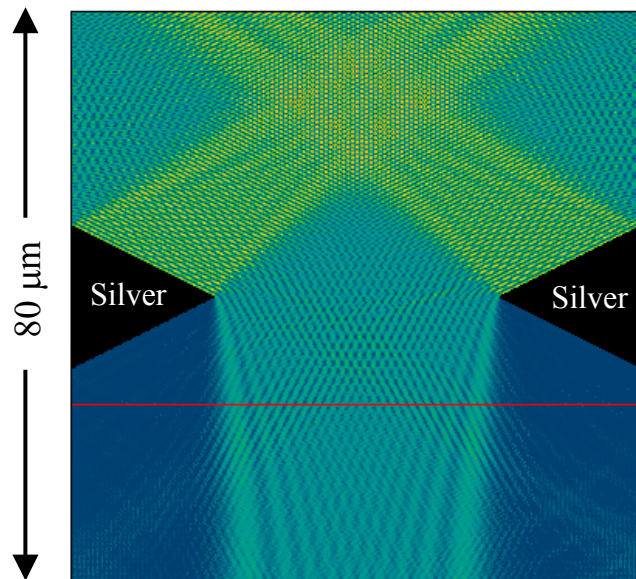
$$E_{Trans}(x) = \int E_{Trans}(\alpha, x) d\alpha$$

- CTF (2D/3D) Requires
Large scale computing
- But once calculated full vector
model can be run on Laptop !
- Allows 6 DOF & aberr beams
- But not deform/manuf errors
requires full model

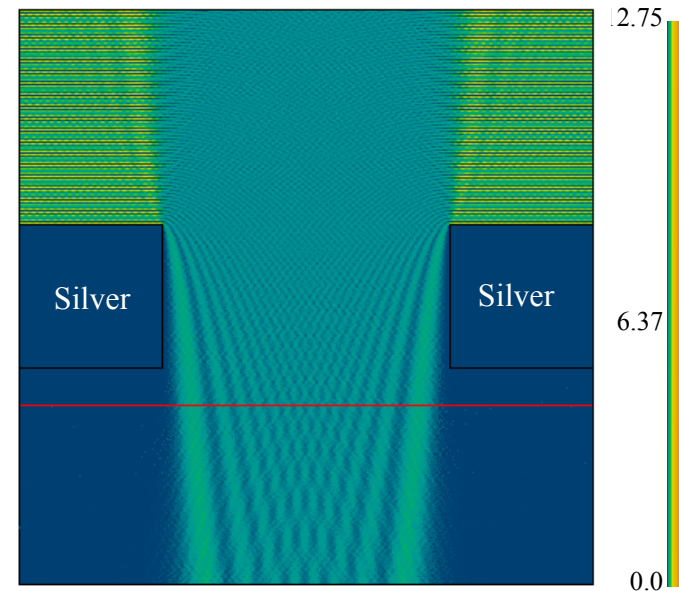




Aperture Edge Effects (Ron Shiri's VOM)

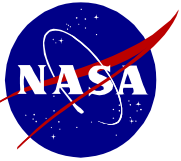


EM FEM Solution, $\lambda = 1$ micron
20 μm thick Silver Bevelled Edge Aperture



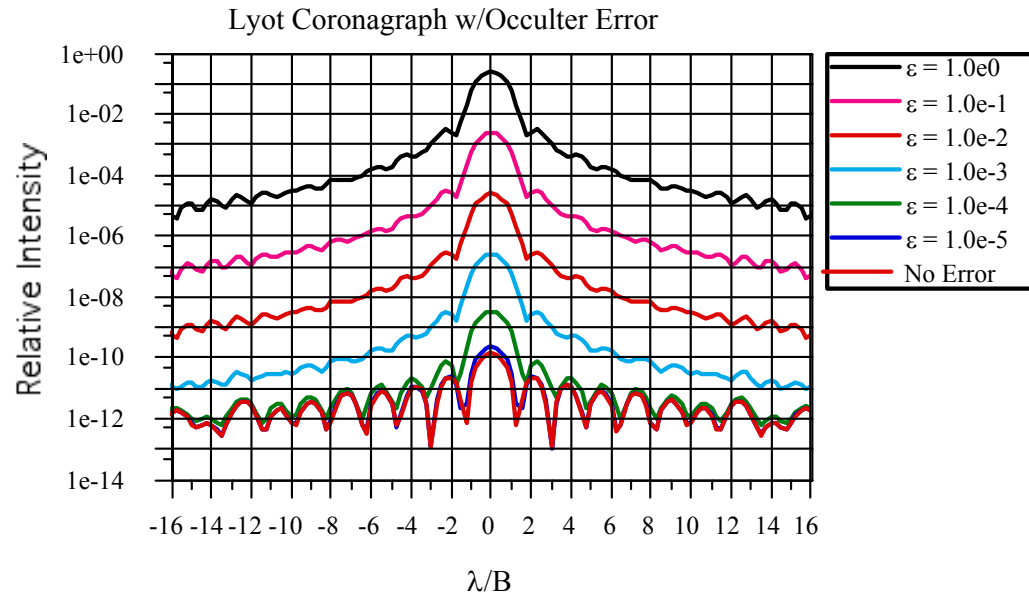
EM FEM Solution, $\lambda = 1$ micron
20 μm thick Silver Square Edge Aperture

- Have to be careful in how edges are made
- Can model diffraction, skin effects, evanescent modes
- Bevelled edges can give wide angle scatter



Occulter Leakage & Diffraction Effects

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Soft-Edge Lyot on-axis PSFs w/Opacity Error

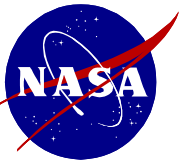
Polychromatic 0.5 - 0.7 microns

70% Lyot stop

The transmission of the occulter is given by:

$$T(r) = 1 - (1 - \varepsilon) e^{-\frac{1}{2} \left(\frac{r}{\sigma} \right)^2}$$

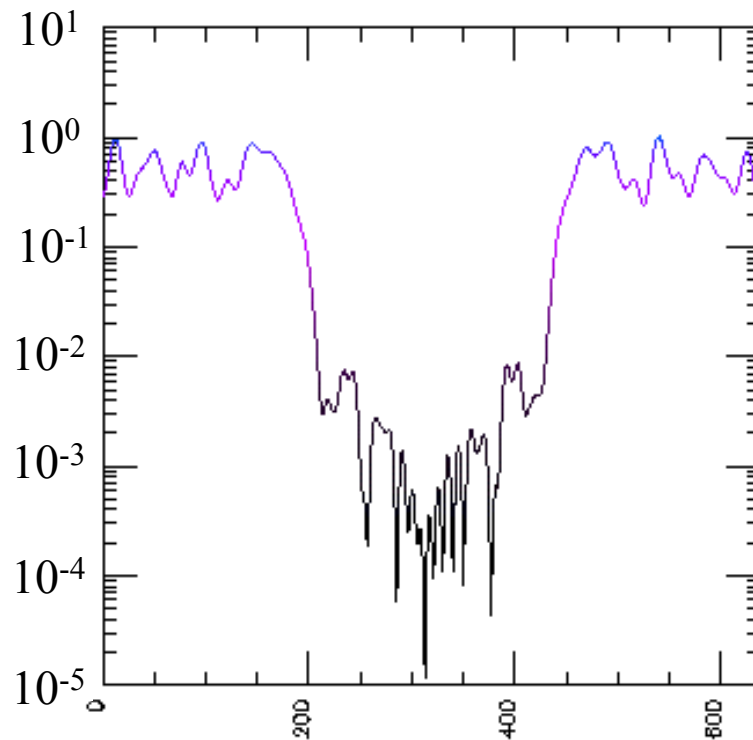
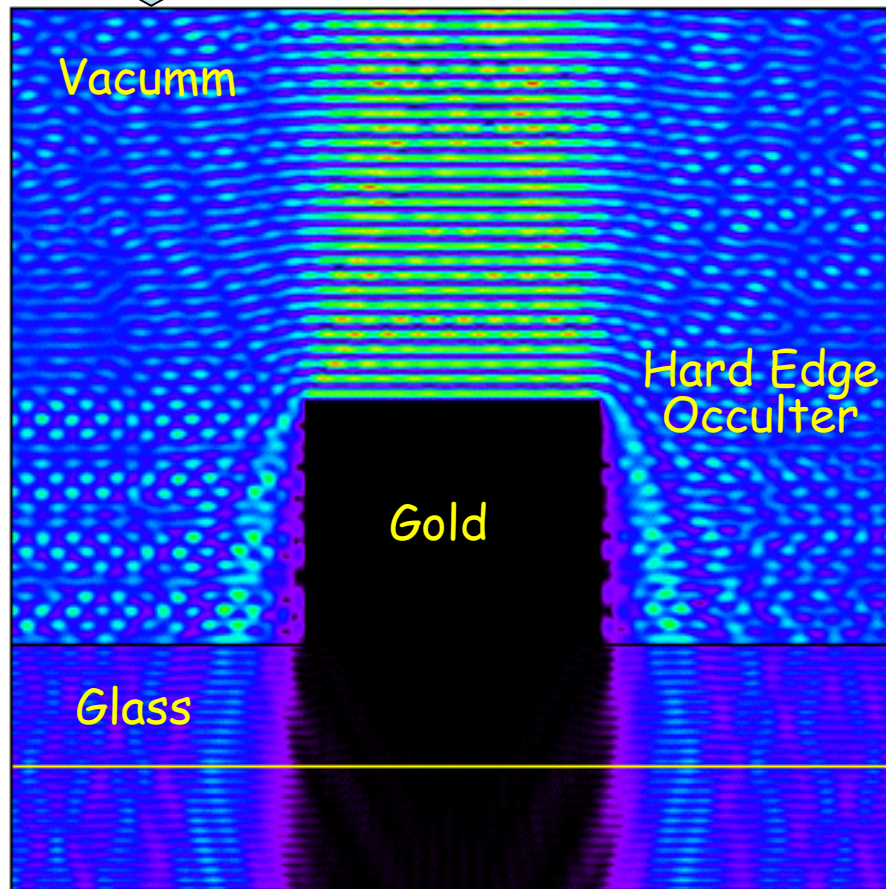
Thus ε is **amplitude opacity**, intensity opacity is $\sim \varepsilon^2$



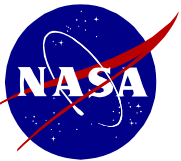
Occulter Leakage & Diffraction

(Ron Shiri's VOM)

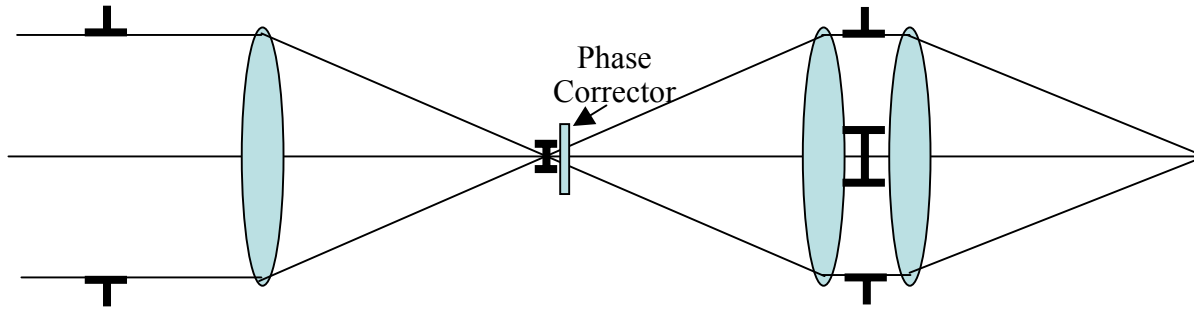
↓ Plane Wave $\lambda = 0.6 \text{ mm}$



$18 \text{ } \mu\text{m}$
 $\lambda = 0.6 \text{ } \mu\text{m}$, 6 μm of Gold thick
on 5 μm of glass, 18 x 18 μm box



Labeyrie Corrector

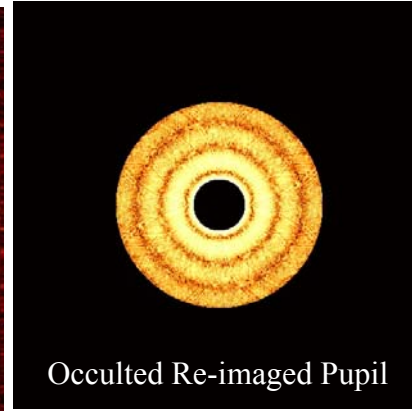
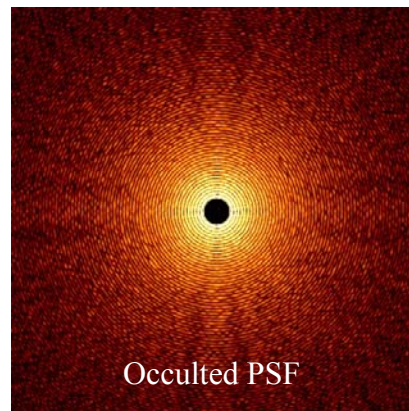
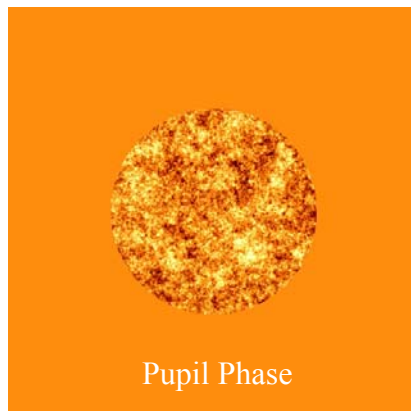
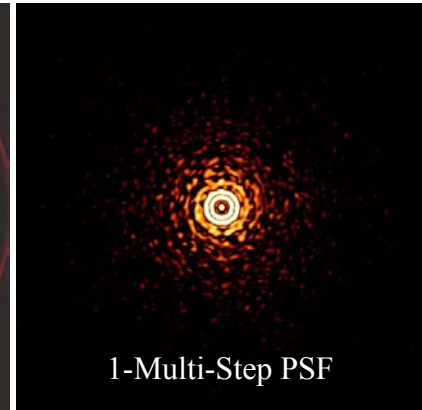
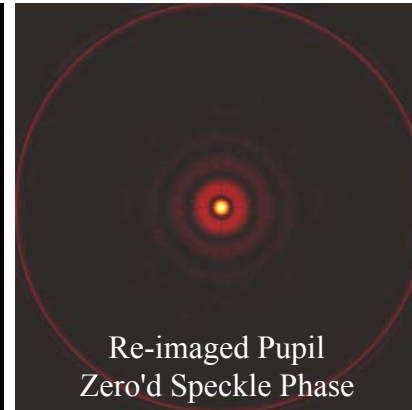
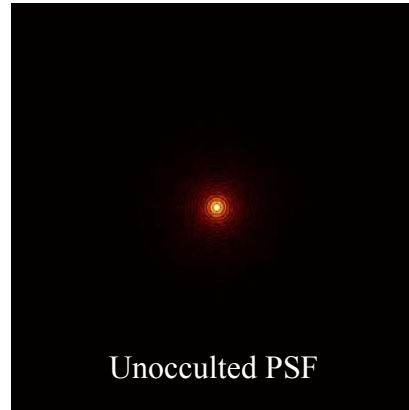
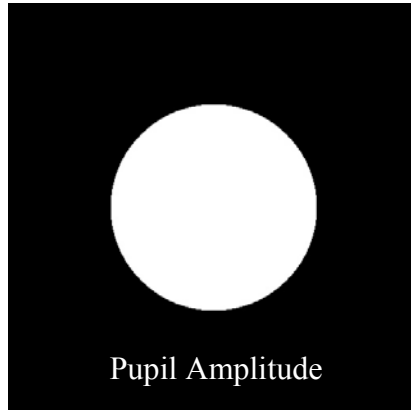


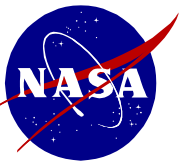
Telescope Exit Pupil
Multi-Stage Entrance Pupil

Focal Plane Occulter
Zero'd Speckle Phase

Re-Imaged Pupil
Pupil Occulter Mask

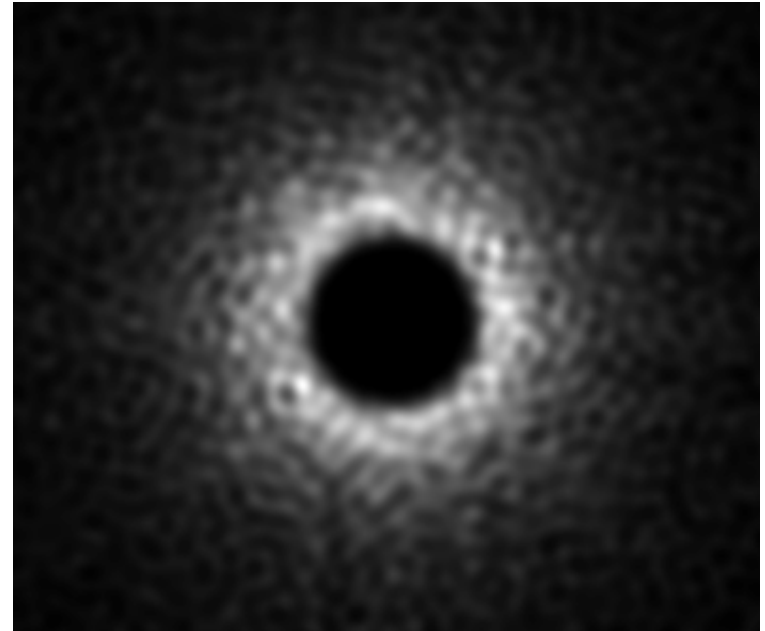
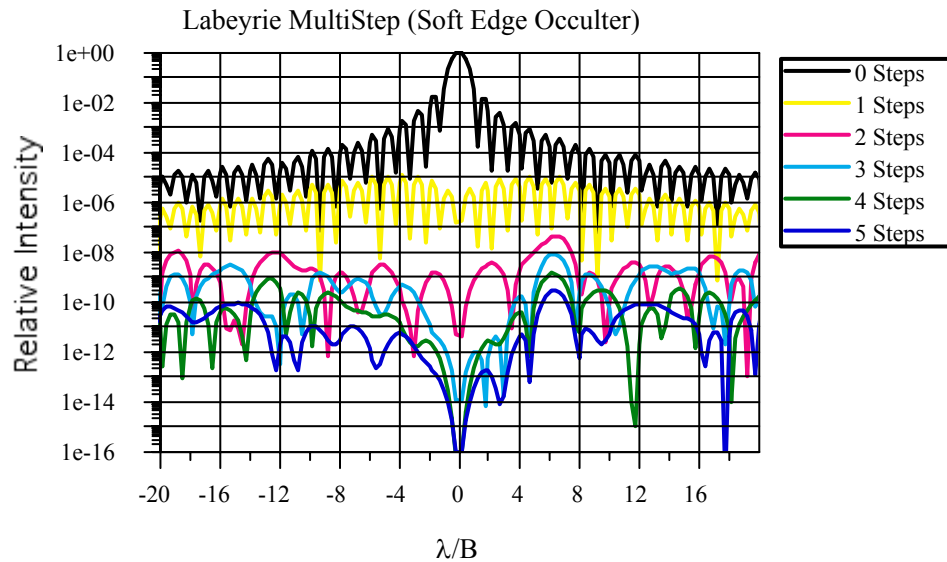
Focal Plane





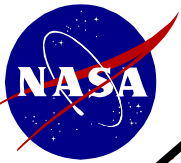
Labeyrie Corrector

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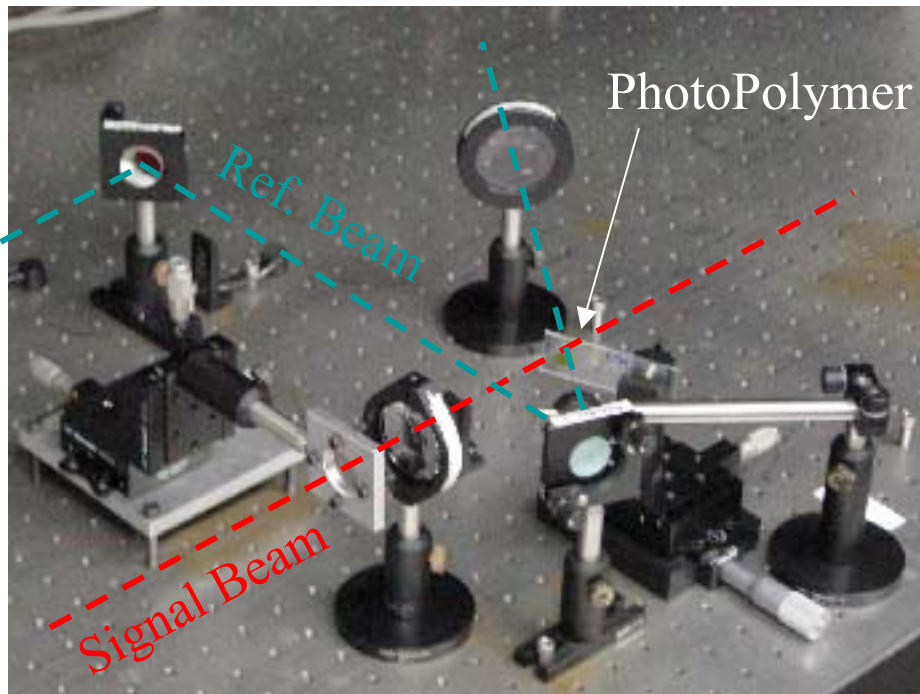
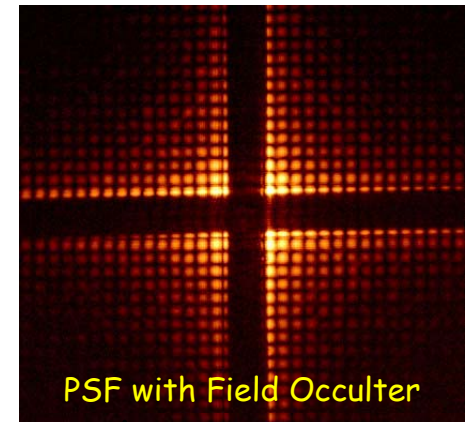
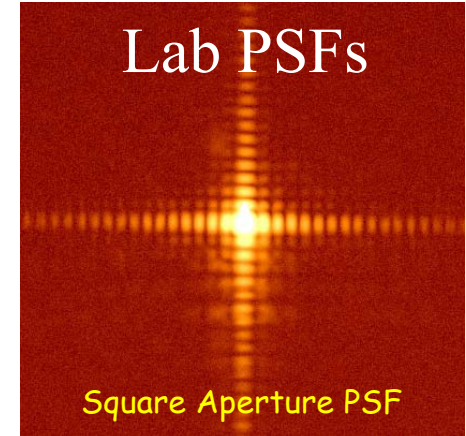
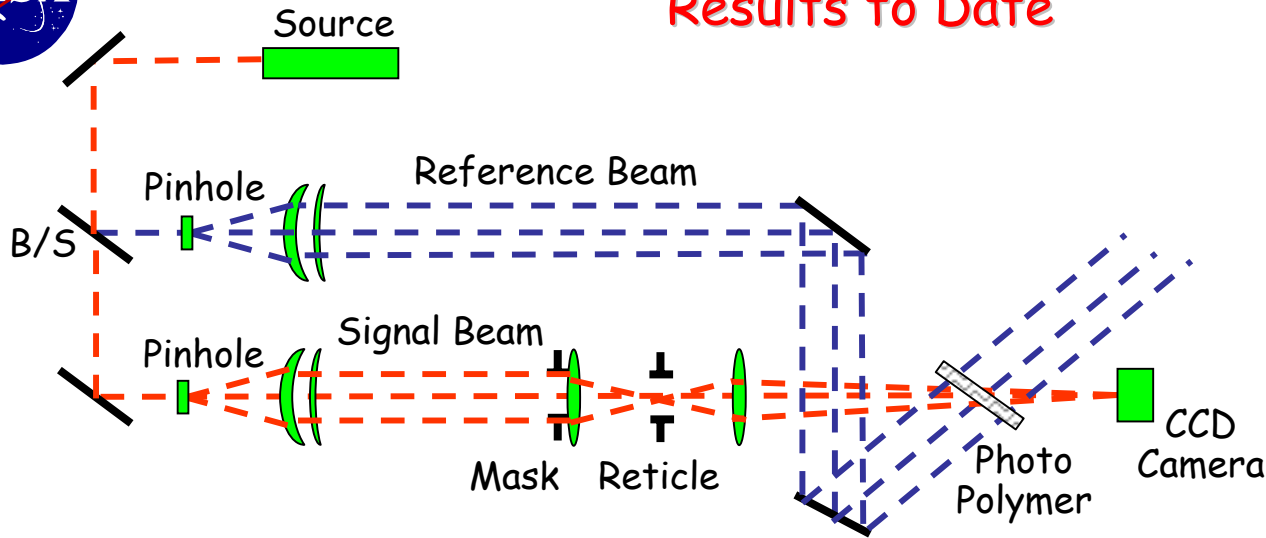
Requires:

- Wavefront sensing of speckle phases
- Correction of speckle phases
need dense DM (or 2 DM method)
- Need to correct speckle phases to $\lambda/8$
- Lowers WFE 1 order magn per step
- Lowers PSF wings ~2 orders of magnitude
- Increases Contrast ~2 orders of magnitude



Holographic Speckle Correction

Results to Date



To Date:

- Built Lab setup (\$70K)
- Manuf & procured photopolymer
- Demo'd Lo-Freq WF Correction
- Next Step: speckle correction
- Out of funds ?
- Can be achromatized !



Summary

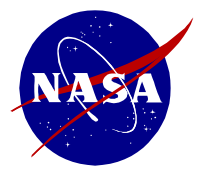
R.G. Lyon
10/15/03

- **Current Models:**

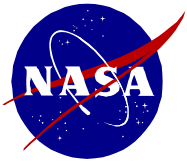
- OSCAR - Optical Systems Characterization and Analysis Research
- Raytrace, Polarization, Pseudo-Nonsequential
- Multiple Diffraction Models: Ang Spect, Fresnel (FFT/Quadrature)
- Filled, Segmented, Interferometric Aperture
- Misalignments, deformations, random surfaces etc...
- Parallel Code (Beowulf Clusters C/MPI)
- Used on previous TPF studies, JWST, Stellar Imager, EASI, etc...
- TPF: ASA/SK/Lyot and External Occulters, HyperTelescopes
- Prep for release through GSFC Tech Commercialization Office.

- **Expansion of Models:**

- Development Technologies for the TPF Mission (JPL JYC-572383)
- 2 years w/ optional 3rd year, Oct 2002 - Oct 2004
- Lyon, Woodruff, Shiri, Antosik
- Expand Models for:
 - Vector Diffraction w/Polarization
 - Vector Finite Element Modeling (R. Shiri)
 - Couple FEM to OSCAR via Component Transfer Functions
- Systems Level Approach => Sensitivities & Error Budgets



Backup Slides



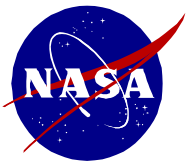
OSCAR

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09/25/03

Optical Systems Characterization and Analysis Research Software

- Multiple plane *diffraction*, Fresnel, Fraunhofer and rigorous Angular Spectrum.
- *Segmented* apertures and *deformable* mirrors, influence functions, range limits, clamped, slaved, floating and constrained actuators models.
- Full- and sub-aperture *Zernike* polynomials.
- power law *random surfaces*.
- White noise, harmonic and low frequency *jitter models*.
- *Detector effects*, MTF, pixelization effects, quantization error, q.e.
- Gaussian and Poisson noise models.
- System *radiometry* spectral filter functions, optics transmission.
- *Coronagraph* capability with assortment of masks and Lyot stops.
- *Scattering*, Surface Scatter, Diamond Turning, Atmosphere
- *Scene Modeling* Fractal landmass, cloud and water models from LEO/GEO and with *scan mirror* options.
- Fizeau and Michelson *Imaging Interferometer* model.
- Polarization raytrace & diffraction
- *Inhomogeneous wave propagation* , (R.Shiri's Ph.D Thesis).
- Shack-Hartmann sensor model etc...

- Disclosed thru TCO
- Currently undergoing release process
- 3 Companies have requested use of OSCAR
- 1 undergoing formal licensing currently



Random Polarization

Classical EM Theory

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10/15/03

- Treat each polarization separately in CTF Calculations
- Thermal source @ Infinity \Rightarrow Plane waves @ Telescope
- Finite source \Rightarrow angular deviation in plane waves
- Each time step \Rightarrow single polarization state

$$\vec{E}(\vec{r}, t) = \hat{x}E_x(\vec{r}, t)\cos\phi(t) + \hat{y}E_y(\vec{r}, t)\sin\phi(t)$$

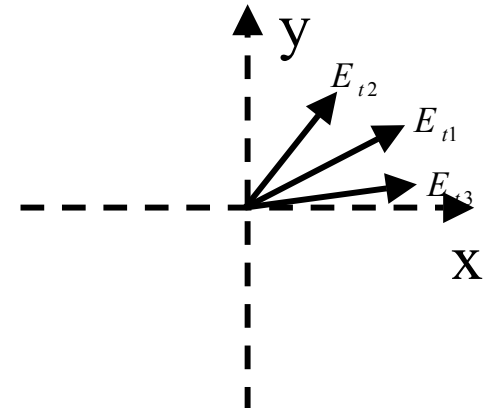
$$\frac{\partial\phi(t)}{\partial t} \ll \omega \quad P(\phi(t)) = \frac{1}{2\pi} \text{rect}\left(\frac{\phi}{2\pi}\right)$$

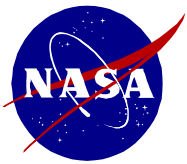
• Intensity:

$$I(\vec{r}, t) = \langle \vec{E}(\vec{r}, t) \cdot \vec{E}(\vec{r}, t) \rangle = E_x(\vec{r}, t)E_x^*(\vec{r}, t)\langle \cos^2\phi(t) \rangle + E_y(\vec{r}, t)E_y^*(\vec{r}, t)\langle \sin^2\phi(t) \rangle$$

$$I(\vec{r}, t) = \frac{1}{2} E_x(\vec{r}, t)E_x^*(\vec{r}, t) + \frac{1}{2} E_y(\vec{r}, t)E_y^*(\vec{r}, t)$$

Treat polarizations separately
Average output results





Vector Optical Modeling Approach

Finite Element Modeling

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10/15/03

Each wavelength independent: $\vec{E}(\vec{r}, t) = \vec{E}(\vec{r})e^{i2\pi\nu t}$

Inhomog Media \Rightarrow Homog D.E. w/non constant coeffs

$$\nabla^2 \vec{E}(\vec{r}) + \nabla(\nabla \ln \epsilon(\vec{r}) \cdot \vec{E}(\vec{r})) + k^2 \epsilon(\vec{r}) \vec{E}(\vec{r}) = 0$$

In each homogenous region solve: $\nabla^2 \vec{E}_j(\vec{r}) + k^2 \epsilon_j \vec{E}_j(\vec{r}) = 0$
w/ boundary conditions:

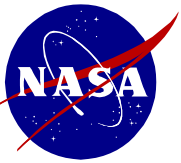
Solve for TE & TM for each plane wave angle and each λ

$$\vec{E}(\vec{k}, z) = E_x(k_x, k_y, z)\hat{x} + E_y(k_x, k_y, z)\hat{y}$$

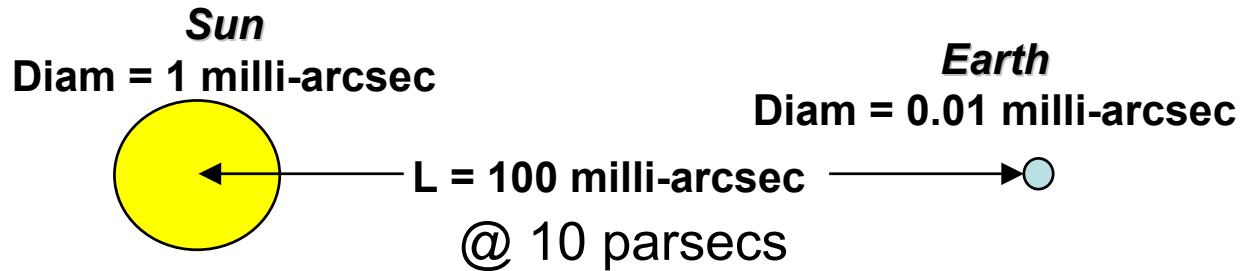
Decompose arbitrary input field into angular plane wave spectrum

$$E_{x,y}(k_x, k_y, z) = \iint E_{x,y}(x, y, z) e^{-i(k_x x + k_y y)} dx dy$$

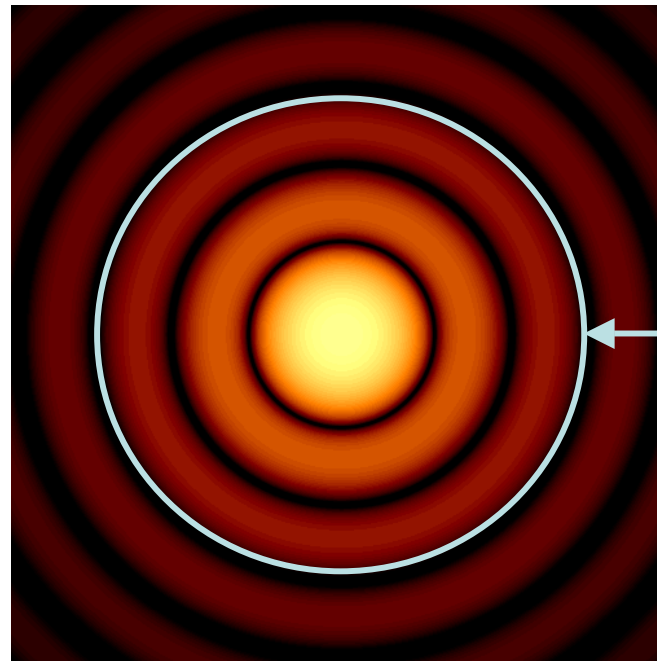
Random Polarization \Rightarrow treat polarization separately



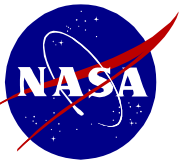
Statement of the Problem



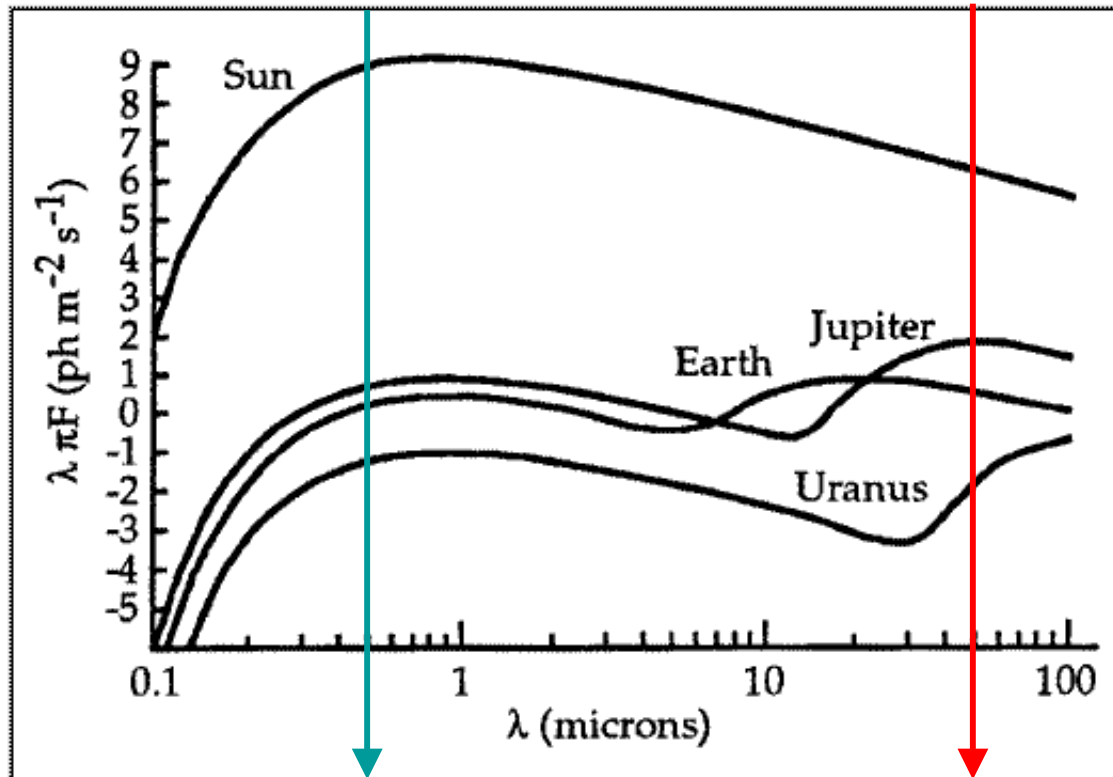
$$\lambda = 0.5 \mu\text{m}$$
$$D = 4.0 \text{ m}$$
$$1.22 \lambda/D = 31 \text{ msec}$$
$$\text{Earth} \sim 3 - 4 \lambda/D$$



Earth's Orbit
Around Sun
@ 10 parsecs



Coronagraph vs Interferometer ?



Visible Light Coronagraphy

Earth: $L_R \sim 10^{-10}$

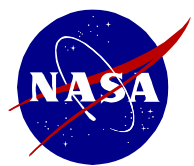
Jupiter: $L_R \sim 10^{-9}$

IR Interferometry

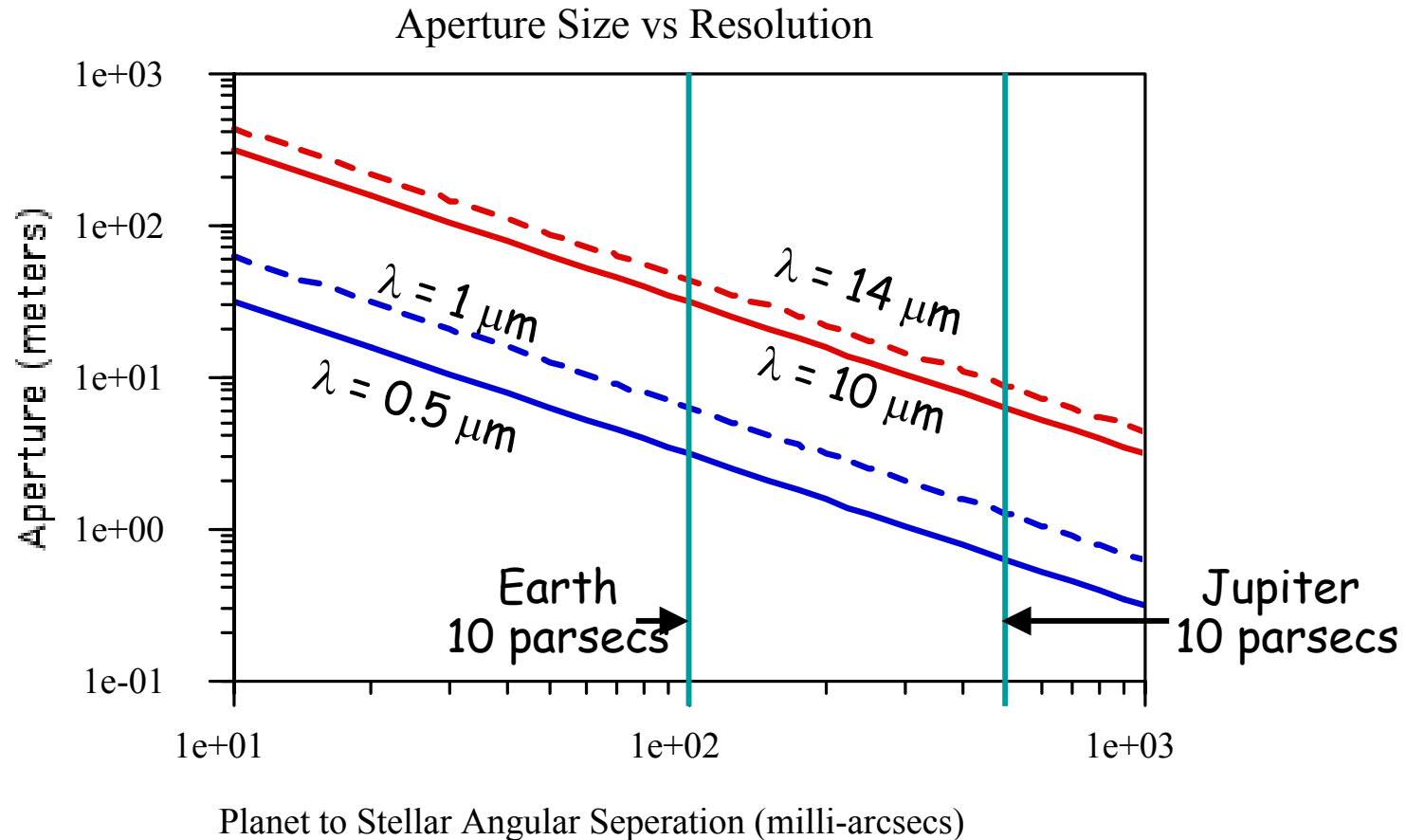
Earth: $L_R \sim 10^{-7}$

Jupiter: $L_R \sim 10^{-5}$

Interferometry => Significant Advantage in terms of Luminosity Ratio



However ?



Visible Light Coronagraphy

Earth: $D \sim 3 - 6$ meters

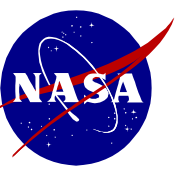
Jupiter: $D \sim 0.62 - 1.25$ meters

IR Interferometry

Earth: $B \sim 30 - 43$ meters

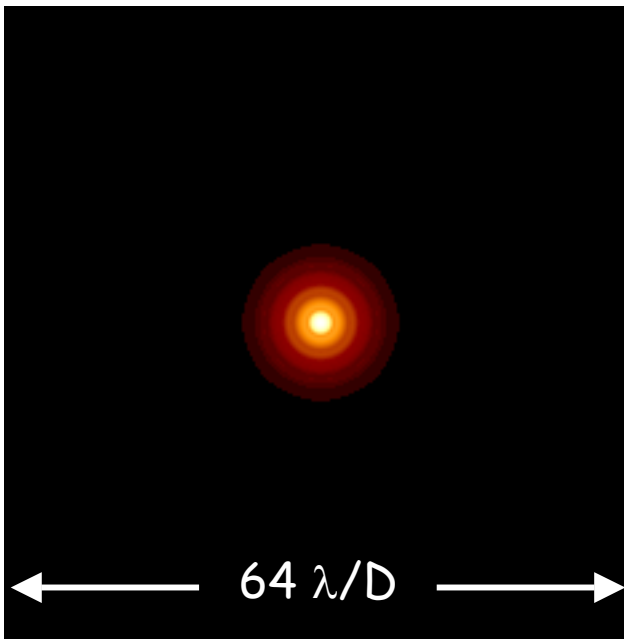
Jupiter: $B \sim 6 - 9$ meters

Coronagraphy => Significant Advantage in terms of Aperture Size



Why We Need A Coronagraph ?

Why not a conventional Telescope ?



The ratio of the planetary flux
to stellar diffracted flux has
Contrast < 1 out to $\sim 1000 \lambda/D$!

